

Mass loss predictions for hot stars

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Abstract. I present the results of radiation-driven mass-loss predictions for hot stars of all mass. Mass loss is an important aspect for the evolution of massive stars, the rotational properties of the progenitors of gamma-ray bursts, and is essential in assessing whether the most massive stars explode as pair-instability supernovae, or avoid them due to mass loss. As a result, the rate of mass loss is critical for our understanding of the chemical enrichment of the Universe. Of particular interest is the question whether luminous blue variables are the *direct* progenitors of some supernovae. Although there is a growing body of evidence to suggest this, it remains as yet unexplained by state-of-the-art stellar evolution models. Finally, I discuss the relevance of mass loss for the appearance and rotational properties of hot Horizontal Branch stars in globular clusters and subdwarf B stars in the field.

Keywords: Mass loss, stellar winds, horizontal branch, luminous blue variables

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INTRODUCTION

The occurrence of stellar winds is ubiquitous for stars of almost all mass and constitutes a key aspect of stellar physics. In terms of the mass loss integrated over a star's life, it is most extreme for the most luminous stars, where the winds are almost certainly driven radiatively. Therefore, I first describe the radiation-driven winds of massive stars, highlighting the implications for the least understood phases of their evolution, e.g. the luminous blue variable (LBV) phase.

The relevance of radiation-driven winds is however not limited to massive stars, but radiation-driven winds are thought to play a role for all types of hot stars, such as the post-AGB stars. Furthermore, certain types of main-sequence A and B stars (the magnetic Ap/Bp stars) show intriguing abundance patterns, which is the result of diffusion in the presence of a weak stellar wind. Similar diffusion and wind effects are likely operating in subdwarf B (sdB) stars and blue horizontal branch (BHB) stars.

But there is more: winds remove not only mass, but also angular momentum. For low-mass stars, I discuss the role of stellar winds for the rotational properties of BHB stars in globular clusters. For massive stars, angular momentum loss is particularly relevant with respect to the long-duration gamma-ray bursts (GRB) phenomenon, as the popular collapsar model requires the GRB progenitor to be rotating rapidly.

Finally, I describe the role of metallicity Z , a key parameter in the physics of stars and galaxies, largely via the metallicity dependence of radiation-driven winds during the main sequence and final phases of stellar evolution.

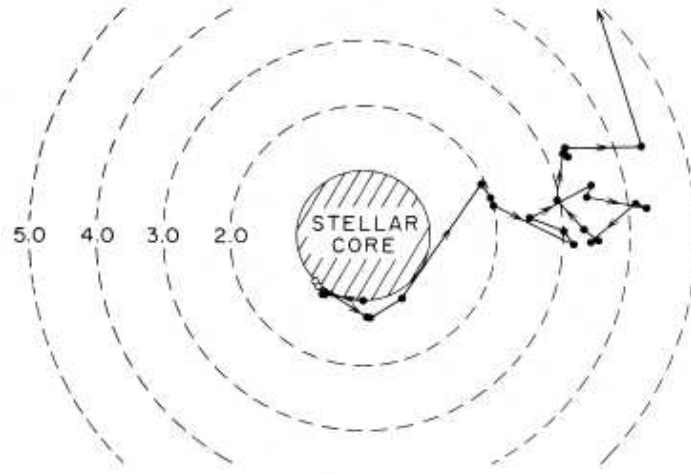


FIGURE 1. The path of a typical Monte Carlo photon that undergoes multiple interactions with matter on its way through the stellar wind, thereby depositing both energy and momentum. Taken from Abbott & Lucy (1985).

PREDICTIONS FOR MASSIVE OB STARS

The evolution of a massive star, with $M > 30 M_{\odot}$, is largely dominated by mass loss. The theory of radiation-driven winds was developed in the early 1970s by Lucy & Solomon (1970) and Castor, Abbott & Klein (1975, CAK). Metal ions, such as Fe, are efficient scatterers of photons at specific line frequencies, and when the resulting radiative acceleration becomes larger than the inward pointing gravitational acceleration, an outflow results. For the dense winds of OB supergiants, Coulomb coupling is highly efficient, and the flow may be approximated as a single fluid (although this assumption may break down for the weaker winds of Horizontal Branch stars).

The early radiation-driven wind models and subsequent non-LTE improvements by e.g. Kudritzki & Puls (2000) have been very successful in reproducing many wind properties. For dense winds however, these modified-CAK models do not suffice, as multiple scatterings are not included (e.g. Abbott & Lucy 1985). Vink et al. (1999,2000) predicted the mass-loss rates of OB supergiants as a function of stellar parameters including the effect of multiple scatterings (on line and continuum opacity) using a Monte Carlo approach (see Fig. 1). The mass-loss rates were found to scale as:

$$\dot{M} \propto L^{2.2} M^{-1.3} T_{\text{eff}}^{-1} (v_{\infty}/v_{\text{esc}})^{-1.3} \quad (1)$$

This shows that the mass-loss rate scales strongly with luminosity ($L^{2.2}$). The reason is that the more luminous stars have denser winds and the MC predictions deliver an increasingly larger mass-loss rate than modified-CAK predictions. The results of Eq. (1) are being widely used in models of massive star evolution ¹.

¹ they can be obtained from <http://www.arm.ac.uk/~jsv/>

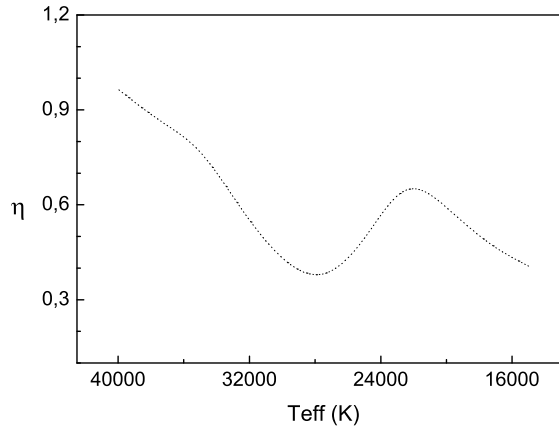


FIGURE 2. Predictions of the wind efficiency $\eta = \frac{\dot{M}v_{\infty}}{L/c}$ as a function of effective temperature. Note the presence of a local maximum around 25 000 K, the bi-stability jump.

Figure 2 shows the predictions as a function of effective temperature, expressed as the efficiency of the momentum transfer, $\frac{\dot{M}v_{\infty}}{L/c}$. The plot shows a declining wind efficiency with effective temperature. At the higher O star temperatures, of $\sim 40\,000$ K, the flux and the opacity show a good “match” and the momentum transfer efficiency is high. When the temperature drops, the flux moves gradually towards lower wavelengths, resulting in a growing mismatch between the flux and the line opacity.

Around 25 000 K, a jump in the mass-loss rate is noted due to an increased Fe opacity. This “bi-stability jump” (Pauldrach & Puls 1990) may recently have been confirmed in radio data that appear to confirm the presence of a local maximum (Benaglia et al. 2007), but the predictions below the jump temperature are much larger than predicted (see the discussion in Vink et al. 2000, Trundle & Lennon 2005, Crowther et al. 2006).

The bi-stability jump occurs where winds change from a low \dot{M} , fast wind, to a high \dot{M} , slow wind, due to a change in the Fe ionisation that drives the wind. It may be an important ingredient for stellar evolution calculations, when stars evolve off the main sequence towards the red part of the Hertzsprung-Russell diagram (HRD). This is not only relevant for their *mass* loss, but also for the loss of *angular momentum*. It may also play a role for LBV mass loss.

THE WINDS OF LUMINOUS BLUE VARIABLES

Figure 3 shows the HRD position of the confirmed galactic and Magellanic Cloud LBVs. The objects change their effective temperatures (and stellar radii) on a variety of timescales with various amplitudes (e.g. Humphreys & Davidson 1994). The so-called *micro* variations are intriguing but similar to other supergiants in this part of the HRD. At the other extreme are the Eta Car-type huge eruptions, also referred to as SN-impostors when they occur in external galaxies (e.g. Van Dyk et al. 2000). We note that only two

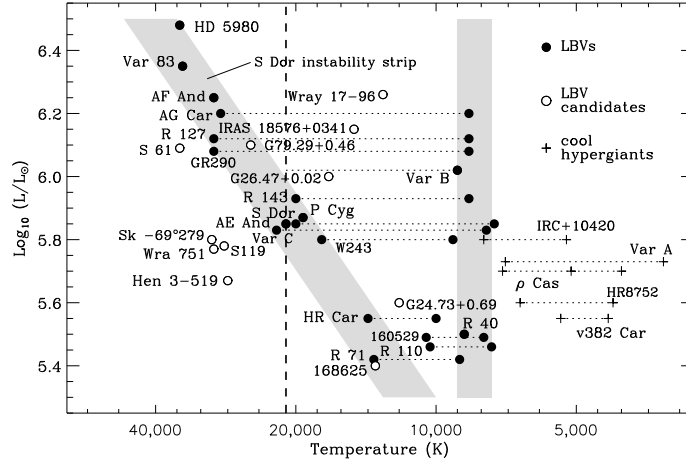


FIGURE 3. The position of luminous blue variables in the HRD. The shaded areas represent the objects during visual minimum (the tilted area on the left) and maximum (the straight vertical area on the right at ~ 8000 K). The dashed vertical line at 21000 K is the position of the bi-stability jump. The figure is adapted from Smith et al. (2004).

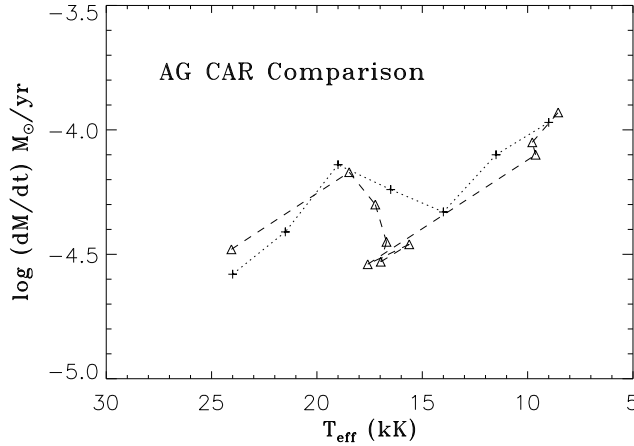


FIGURE 4. The dashed line represents variable mass-loss predictions for LBVs vs. effective temperature. Also shown (dotted line) are the empirical mass-loss rates for AG Car analysed by Stahl et al. (2001).

giant outbursts have ever been recorded in the Galaxy (the eruptions of Eta Car in the 19th and P Cyg in the 17th century). Most typifying for LBVs as a class are the S Dor variations. For this variability, the amplitudes vary on timescales of years to decades (e.g. van Genderen 2001).

When LBVs such as AG Car – one of the prototype S Dor variables – change their radii on their S Dor timescales, they show large mass loss variations (Stahl et al. 2001). Such variable wind behaviour has qualitatively been reproduced by radiation-driven

wind models of Vink & de Koter (2002) as depicted in Fig. 4.

We anticipate that this type of wind behaviour may result in a circumstellar medium consisting of concentric shells with varying densities. This may have ramifications for the end-points of massive stars. Kotak & Vink (2006) recently suggested that the quasi-periodic modulations seen in the radio lightcurves of some supernovae (SNe), such as 2001ig (Ryder et al. 2004) and 2003bg (Soderberg et al. 2006) may indicate that LBVs could be the *direct* progenitors of some SNe. At first this seems to contradict stellar evolution calculations, which do not predict LBVs to explode, and such a scenario was until recently considered “wildly speculative” (Smith & Owocki 2006). Nevertheless, the recent case of SN 2006jc that showed a giant eruption just 2 years before it exploded (Pastorello et al. 2007, Foley et al. 2007) may add confidence to our suggestion, although there are unresolved issues with the chemical abundance of 2006jc and its progenitor. There are other tantalising indications that LBVs may explode. Gal Yam et al. (2007) may have detected a very luminous progenitor of SN 2005gl, although it remains to be seen if this is a single object. Although the properties of the potential progenitor star are consistent with that of an LBV, a hypergiant cannot be classified as an LBV until it has shown S Dor or Eta-Car-type variability. A final interesting hint that LBVs may explode comes from the striking similarities in LBV nebula morphologies and the circumstellar medium of SN 1987A (Humphreys & Davidson 1994, Smith 2007).

As current state-of-the-art stellar evolution calculations do not predict LBVs to explode, this represents a major unresolved problem in the physics of massive stars.

STELLAR WINDS ON THE HORIZONTAL BRANCH

Moving our discussion to a group of lower mass evolved hot stars, we arrive at objects on the HB. HB stars are low-mass stars with a helium core of about half a solar mass and a small hydrogen layer on top. Vink & Cassisi (2002) provided maximal (where the terminal wind velocity equals the escape velocity) mass-loss predictions for HB stars:

$$\dot{M} \propto L^{2.1} M^{-1.1} T_{\text{eff}}^{-1} Z^1 \quad (2)$$

The predicted rates may account for the remaining mass-discrepancy in BHB stars (Vink & Cassisi 2002, Moehler et al. 2003) whilst at the same time accounting for the observed H α profiles of luminous SdB stars (Vink 2004, Heber et al. 2003). Stellar winds may also be required to explain the complex abundance patterns found in these stars and mass loss may have implications for the angular momentum evolution on the HB.

Figure 5 shows a compilation of rotational velocities of HB stars in globular clusters as a function of effective temperature (Behr et al. 2000). For stars cooler than $\sim 10\,000$ K, there is a spread of slow and rapid ($v \sin i = 40$ km/s) rotators, whilst for temperatures hotter than $\sim 10\,000$ K, *all* HB stars rotate slowly (see also Brown & Salaris, these proceedings). The temperature of this transition coincides with the onset of radiative diffusion where the Fe abundance of initially metal-poor BHB stars increases by a factor of 100. According to Eq. 2, the mass-loss rate may also increase by up to 2 orders of magnitude as a result. Vink & Cassisi (2002) argued that this large increase in mass-loss provides a natural explanation for the low rotational velocities of HB stars hotter than $\sim 10\,000$ K due to angular momentum loss.

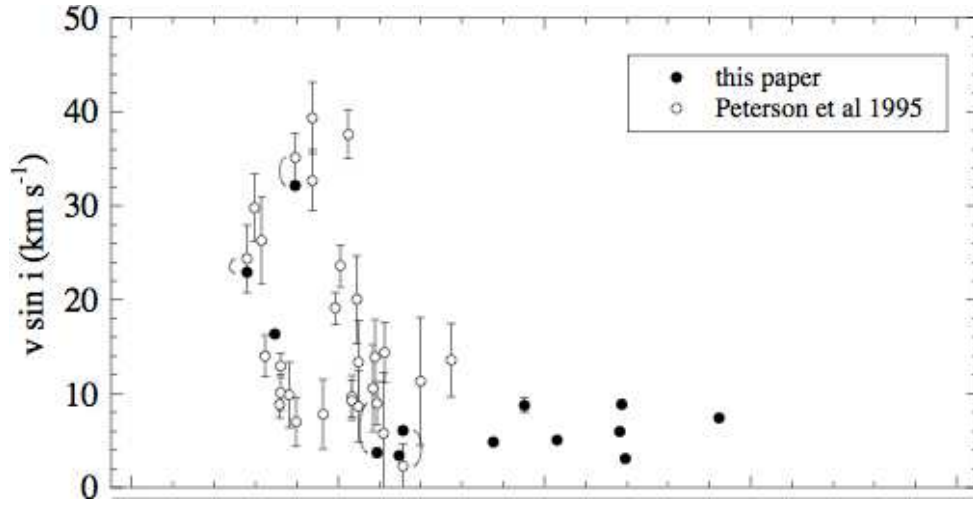


FIGURE 5. Rotational velocities of HB stars as a function of effective temperature. Note that all BHB stars hotter than $\sim 10\,000$ K are rotating slowly. Figure adapted from Behr et al. (2000).

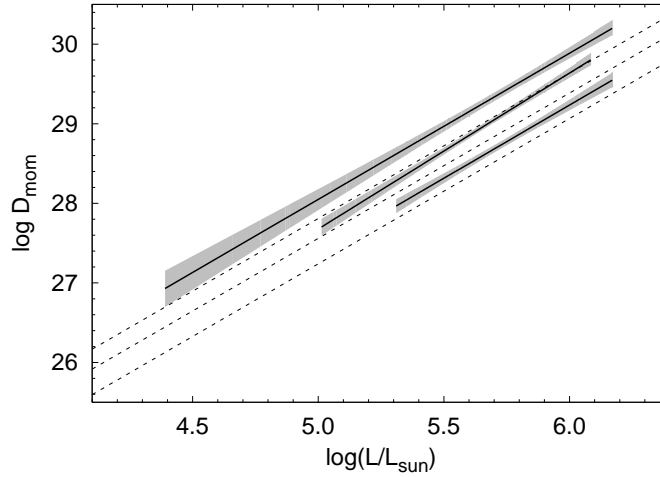


FIGURE 6. This figure represents a confrontation between O star mass-loss predictions (dashed line) and recent empirical mass-loss rates in the form of the so-called wind momentum-luminosity relationship for Galactic (top), LMC (middle) and SMC (bottom) O stars. The figure is from Mokiem et al. (2007).

MASS LOSS AS A FUNCTION OF METALLICITY

Metallicity, Z , is a key parameter in the physics of stars, galaxies, and the cosmos, via metallicity-dependent stellar winds. Figure 6 compares the predictions of O star mass-loss (Vink et al. 2001; dashed line) with recent empirical mass-loss estimates of Mokiem et al. (2007) in the form of the modified wind momentum-luminosity relationship, D , for Galactic, LMC, and SMC O stars in the Z range solar to $1/5$ solar. The modified wind momentum is constructed from the multiplication of the rate of mass loss and the terminal wind velocity modified by the stellar radius (see Kudritzki & Puls 2000).

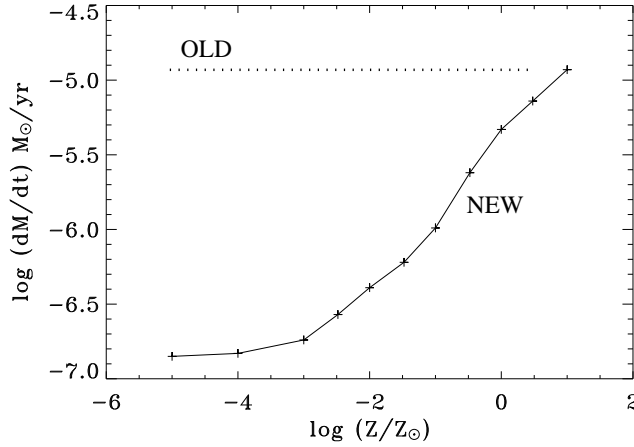


FIGURE 7. The first Z -dependent mass-loss predictions for Wolf-Rayet stars (Vink & de Koter 2005). Despite the overwhelming presence of carbon for all Z , the new WR mass-loss rate does *not* show a Z -independent behaviour as assumed previously (see dotted line). Instead, the new computations show that WR mass loss depends strongly on iron (Z) — a *key* result for predicting a high occurrence of long-duration GRBs at low metallicity.

It can be noted that for all three galaxies (Milky Way, LMC, SMC), the empirical rates are larger than predicted by theory. As the empirical rates are most likely affected by wind clumping, the empirical rates are likely maximal. If we assume a modest clumping factor with a corresponding reduction in the empirical \dot{M} by a factor 2-3, the empirical rates show good agreement with the wind models. The wind clumping factor however remains an unsolved problem in stellar astrophysics and if the true wind clumping is larger than assumed, with empirical \dot{M} overestimates of ~ 10 as some studies (e.g. Fullerton et al. 2006) suggest, then the current mass-loss predictions might also be too large. This is an important topic for further investigation.

Massive stars lose mass at the most extreme rates during the Wolf-Rayet (WR) phase. In this phase, the outer layers become chemically enriched, which may modify mass loss through winds. We have recently performed a study of mass loss versus Z for late-type WR stars using the Monte Carlo approach. The outcome is shown in Fig. 7. Despite the overwhelming presence of carbon at all Z , \dot{M} does *not* show a Z -independent behaviour (as usually assumed previously), but WR mass loss depends strongly on iron (Fe).

Furthermore, although the \dot{M} versus Z dependence is consistent with a power-law decline in the observable Universe down to $\log Z/Z_{\odot} \sim -3$, it flattens off for extremely low Z models. The reason is that carbon, nitrogen, oxygen, hydrogen and helium take over the driving due to iron (Fe) which is dominant at high Z .

The strong Z -dependence of WR winds shown in Fig. 7 where the WR \dot{M} drops by orders of magnitude, represents a key result for the high frequency of long-duration GRBs at low metallicity. The favoured progenitors of long-duration gamma-ray bursts (GRBs) are rapidly rotating Wolf-Rayet (WR) stars, however, most Galactic WR stars are slow rotators, as stellar winds are thought to remove angular momentum, which may pose a challenge to the collapsar model for GRBs. Observational data however indicate

that GRBs occur predominately in low metallicity (Z) galaxies (e.g. Stanek et al. 2006), which may resolve the problem: lower Z leads to less mass loss, which may inhibit angular momentum removal, allowing WR stars to remain rotating rapidly until collapse (Yoon & Langer 2005, Woosley & Heger 2006).

As a test of this scenario, Vink (2007) performed a linear spectropolarimetry survey of WR stars in the low Z environment of the LMC and found an incidence of line polarisation effects in LMC WR stars as low as that of the Galactic sample of Harries et al. (1998). This suggests that the threshold metallicity where significant differences in WR rotational properties occur is below that of the LMC (at $Z \sim 0.5 Z_{\odot}$), possibly constraining GRB progenitor channels to this upper metallicity.

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